

HIGHLIGHTS OF NASA'S ROLE IN DEVELOPING STATE-OF-THE-ART NONDESTRUCTIVE EVALUATION FOR COMPOSITES

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ABSTRACT

Since the 1970's, when the promise of composites was being pursued for aeronautics applications, NASA has had programs that addressed the development of NDE methods for composites. These efforts included both microscopic and macroscopic NDE. At the microscopic level, NDE investigations interrogated composites at the submicron to micron level to understand a composite's microstructure. A novel microfocus CT system was developed as well as the science underlying applications of acoustic microscopy to a composite's component material properties. On the macroscopic scale NDE techniques were developed that advanced the capabilities to be faster and more quantitative. Techniques such as stiffness imaging, ultrasonic arrays, laser based ultrasound, advanced acoustic emission, thermography, and novel health monitoring systems were researched. Underlying these methods has been a strong modeling capability that has aided in method development

INTRODUCTION

NASA has promoted composite technology development during the past several decades because of the large anticipated impact that composites would have on aeronautics and aerospace. As a consequence, today, composites are being used increasingly in airframe and space structures. In conjunction with the increase use of composites, there has been a need to develop the NDE infrastructure to help certify those composite structures.

The mechanics of composite structures are better understood today than 25 years ago. Over that time

period, many innovations in materials and manufacturing methods for composites have occurred. Accompanying those innovations have been challenges for NDE to address. Simultaneously, instrumentation technologies have also progressed, providing new opportunities for NDE developments that could be applied to composite testing.

Early in the development of composite technology by NASA, it became clear that there were very fundamental questions about the microstructure of a composite. This microstructure not only affected the strength and mechanical properties of composites, but the microstructure also affected the quality of NDE signals, which have an impact on the interpretation of NDE results. That suggested that NASA needed to try to develop and apply technologies that could address microstructural questions as well as develop macroscopic technologies that could deal with microstructural effects. In addition, as composite components became more and more ubiquitous in airframes and spacecraft, there has been a need for NASA to invest in research that could lead to cost effective NDE technologies for scanning parts quickly and providing quantitative information about the quality of the part. To attain our goals required a program that integrating experimental techniques with a strong modeling effort in all of the NDE technologies pursued, including, radiography, ultrasonics, thermography, electromagnetics and optics.

MICROSCOPIC NDE

One very unique system that NASA established was

a microfocus CT system built on a load frame entitled the **QU**antitative **E**xperimental **S**tress **T**omography or QUEST. [1] The specification for this system is an x-ray CT system with 12.5 μm pixel resolution. The minimum slice thickness is 50 μm . The part under test can be stressed up to 50 Kips, which allows researchers to interrogate the interior of a sample while it is under load. Some examples of composites that have been scanned by this system are shown in Fig. 1. That figure shows the cross-sections of two composite samples. Figure 1a shows a corner of a Y-stiffened graphite epoxy composite component that has suffered impact damage. Numerous cracks and delaminations, as well as glass microspheres are visible in that figure. Figure 1b shows a composite hat stiffener. In that figure, the laminate weave and porosity are visible. The QUEST system has been successful in imaging and quantifying porosity, stitching materials, inclusions, debonding, material loss, and other microscopic flaws in materials. The ability to image the internal structure and flaws of a composite at such a microscopic scale has been critical in the research of material scientists.

Additional unique capabilities that have been established at NASA Langley Research Center are a **S**canning **E**lectron **A**coustic **M**icroscope or SEAM and a **S**canning **A**coustic **M**icroscope or SAM. These technologies allow one to view a part's surface and subsurface microstructure with a resolution of a fraction of a micron. Instead of an optical image, an image that is related to thermo-elastic properties is produced. An example of this capability was to image surface and subsurface cracks and residual stresses on assorted fiber fractures. [2] Fig. 2 shows two examples of acoustic microscopy. The first example dealt with fiber fractures. Normally, photoelastic methods are used to identify the fracture spacing of a fiber in a matrix. This information can then be used to predict the strength of a fiber in a matrix. With SAM imaging, researchers were able to show that fiber lengths were actually shorter because of fiber matrix fracturing that released the strains on the fibers' end as seen in Fig. 2a. This provided a much more accurate estimate of fiber strength. Also, efforts have been made to try to use SAM imaging to quantitatively characterize the fiber matrix interface in composites and to characterize the elastic properties of silicon carbide fibers microscopically as shown in Fig. 2b. [3, 4]

MACROSCOPIC NDE

As instrumentation and computational capabilities have improved, many opportunities to advance NDE methods have become possible. In ultrasonics, NASA has worked on methods to image material properties such as stiffness. In one example shown in Fig. 3, a radiograph image of a carbon-carbon brake stator is shown with an image of the C_{33} stiffness map for the same part. [5] In that work, images of all 9 coefficients (orthotropic symmetry) were calculated from ultrasonic measurements. In Fig. 3b, the C_{33} image indicates a region with a stiffness loss. This type of imaging was then coupled to FEM codes to predict local stress and strain responses in that part. [6] Subsequent strain measurements corroborated the predictions, including the loss in stiffness measurements. In a parallel research effort, NASA investigated the ability of Lamb wave measurements to track material durability. In that research, several bending and out-of-plane stiffness coefficient images were extracted from Lamb wave measurements made periodically on a series of composite plates undergoing thermal and stress cycles similar to thermal and stress cycles from supersonic flight. [7, 8] Fig. 4 shows the out-of-plane measurements for an unaged thermoplastic composite panel and a panel aged for 10,000 hours of cycling. In Fig. 4, images comparing the A_{55} out-of-plane coefficient clearly indicate the stiffness loss. More results showing the differences of A_{55} , D_{11} , A_{44} , and D_{22} are displayed in Table 1.

In composite parts, the use of ultrasonic phased arrays to inject and extract signals appears to be a viable improvement over conventional transducers which are affected by the composites' inhomogeneous structure. That knowledge has led to the development of a phased array technology program. The **U**ltrasonic **P**hased **A**rray **T**estbed **S**ystem (UPATS) was developed to allow NASA to research the application of phased arrays to composites. [9] That system consists of 100 independent channels. Each channel has its own arbitrary waveform generator with variable gain and delay for transmission and a variable gain and delay for reception with an 8 bit, 50-MHz digitizer, with averaging capabilities. The UPATS can be used to operate linear arrays, circular arrays, rectangular arrays, or specially shaped arrays. It can be used to

investigate focussing algorithms on transmit and receive, beam shape or aperture control, time reversal, and scattering fields. For example, a circular ring array was used to measure the scattered field from a composite sample. Fig. 5 shows the angular results of images made from that system. The sample was a simple uniaxial circular cylinder composite with the fibers perpendicular to the axis. In Fig. 5a, the incoming beam was perpendicular to the fibers and in Fig. 5b, the incoming beam was parallel to the fibers. The differences are quite distinct between the scattered fields.

A third ultrasonic effort has been in developing non-contacting, large area, scanning, ultrasonic systems such as laser based ultrasound. Early commercial systems were generally confined to controlled access areas for safety. Under NASA's program, efforts were made to confine the laser light to fiber optics to make a safe scanning system that could be used in a more open environment. [10] An example of a scan of an impacted thick composite plate produced an image that was similar to the image made with a conventional submersion scanning system and is shown in Fig. 6. In that image, the large impact area is easily seen. Also, lines of through-the-thickness stitching are easily identified. Another effort has been to develop systems that incorporate laser diodes that are small and compact. [11] As a signal generator, the laser diode can be used by modulating its output and then cross-correlating the received signal with the generation signal to recover the system's response function. The advantage is that the light level is less likely to damage the part's surface.

An additional ultrasonic contribution was work to develop high temperature ultrasonic transducers. Research was conducted to produce a piezoelectric transducer that could work in a hostile environment. Figure 7 shows one such system. Figure 7a illustrates how the assembly would be attached to a composite pultrusion system. Figure 7b shows the transducer subassembly in an expanded view. This development has helped with efforts to perform cure monitoring and was successfully demonstrated in a composite pultrusion system. [12]

In the field of acoustic emission (AE), NASA Langley has developed better methods for locating and identifying damage. [13, 14] The work takes into account the fact that several plate modes can be

generated during an AE event. These different modes will travel at different rates and with different amplitudes. Failure to appreciate this fact will result in significant errors in the AE event location. Analysis of the different acoustic modes can yield improved noise discrimination and damage mode identification. In Fig. 8, locations of cracks that were predicted by this advanced AE technique and then measured optically are compared. The results show that all cracks initiated along the specimen edge, with 70 % initiating along the unpolished edge. There was a one to one correlation with the AE crack signals and measured cracks with excellent location results, a maximum of 3.2 mm error out of 152 mm.

In support of NASA's efforts to perform NDE, NASA has supported a significant computational modeling program. That program has been an underlying effort in all of the NDE technologies that NASA has investigated, including, radiography, ultrasonics, thermography, electromagnetics and optics. One area that has benefited significantly from modeling has been thermography. In particular, modeling has allowed the more rapid development of quantitative thermography. As seen in Fig. 9, modeling of thermal images has shown how different algorithms will compute the area of a flaw. Other algorithms can be used to try to predict the depth of the flaw in a composite from thermal data. [15, 16] These methods are proving valuable in locating flaws and defects in composites.

Experimentally, a significant effort has been made to develop thermal NDE techniques for composites. An example of evaluating low velocity impacts in composite missile tubes is shown in Fig. 10. In that study, the area of the underlying damage as measured with thermography is seen in Fig. 10a. In Fig. 10b, the correlation between burst strength and impact damage area as measured by thermography is shown. [17]

Recently, a new method to increase the speed of thermography measurement was developed. The key to this improvement was the use of a thermal line scanner. The method allows for fast inspection times, (Speed greater than 2 in./sec. for composite materials.) easy implementation on robotic or automated systems, simple analysis, archival of data, and also increases signal to noise. Results indicate good sensitivity to water intrusion in honeycomb materials, debonding, impact damage,

and material loss due to corrosion or erosion. [18, 19] Additionally, that method has been used to measure the thermal diffusivity of composites to show the effect of porosity (Fig. 11) and cut fibers (Fig. 12). In those instances, in-plane diffusivity is sensitive to both cut fibers and porosity, while out-of-plane diffusivity is less sensitive to cut fibers.

NASA's optical NDE efforts have centered on fiber optic sensors. Most of this effort has been directed toward structural health monitoring. Currently a very successful effort has been the development of fiber optics with dense Bragg gratings that can measure strain or temperature. NASA's method is different than wavelength division multiplexing where the Bragg grating density is limited to tens of sensors per fiber. The Langley Research Center Demodulation method allows the placement of several thousand sensors per fiber. [20,21] Figure 13a shows a test on a Rockwell Northrop Grumman wingbox. Two optical fibers were used to make strain measurements at 16 locations along the web and spar caps and were bonded to the wingbox. Figure 13b shows the correlation between a fiber optic strain sensor, a conventional strain sensor and the theoretical strain expected at one location. In a later composite wing test, 3000 sensors in 4 fibers were attached and measurements were made while the wing was stressed to its ultimate limits. This technology has also been demonstrated on the Dual Lobe Tank of the experimental X-33 spacecraft. On that vessel, 4 fibers were attached with a total of 53 strain measurements. NASA has also been demonstrating several integrated health monitoring systems, including the NASA high density Bragg grating fiber optics on an F-18 being used to perform risk mitigation for the X-33 program.

FUTURE WORK

As NASA looks to the future, there are numerous programs in place to lead the way in composite NDE. NASA intends to continue its effort in composite research with its program in Smart Health Monitoring Systems. In the area of Space NDE, NASA will need Telerobotic Inspection and Repair capabilities and Autonomous Systems. The concept in those programs is not to just make a system to repair, but build a system that can perform the diagnostics and then make repairs independent of humans. Those types of systems may require Multi-mode Data Fusion, another NASA program. NASA's Nano sensors technology program should help to

develop smaller and lighter systems. Industry's efforts to use bonding of composites in more and more systems have highlighted a need to perform research in Quantitative Bond Strength Sensors. Finally, modeling will continue to be developed under programs such as Virtual Reality NDE Simulations in Design and Virtual Reality NDE Process Control Simulations

CONCLUSION

This paper outlines some of the advancements of NASA's NDE program over the past two decades that have played and are playing a role in composite NDE. At NASA, there has been a need to view composites at the microscopic level as well as a macroscopic level. NASA Langley Research Center has looked at technologies that provide improved speed of measurement and improved quantitative accuracy. Technologies have included radiography, Scanning Acoustic Microscopy, Scanning Electron Acoustic Microscopy, stiffness imaging, phased array ultrasound, laser based ultrasound, high temperature sensors, advanced AE, thermography, linescan thermography, thermal diffusivity imaging, and high density fiber optic Bragg gratings for strain and temperature measurements. Underlying all these technologies, has been a strong modeling capability that has aided in method development.

NASA's future directions represent exciting opportunities. New programs will address a new level of miniaturization, integrated health monitoring, autonomous systems, and telerobotic inspection and repair capabilities. Efforts in modeling based on virtual reality simulations for NDE and process control will lead to new capabilities. Finally, quantitative bond strength sensors and systems will provide valuable capabilities.

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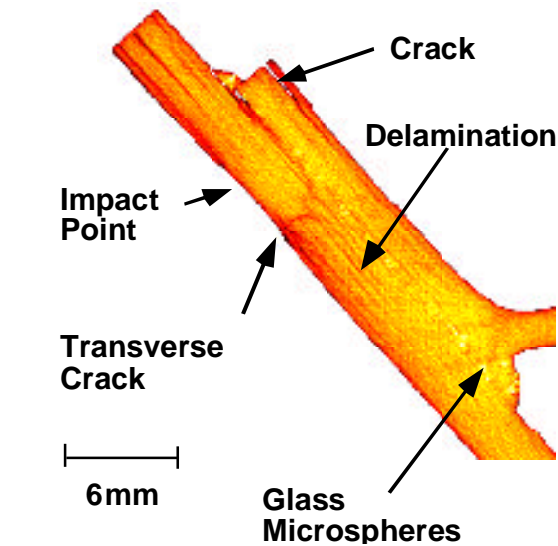
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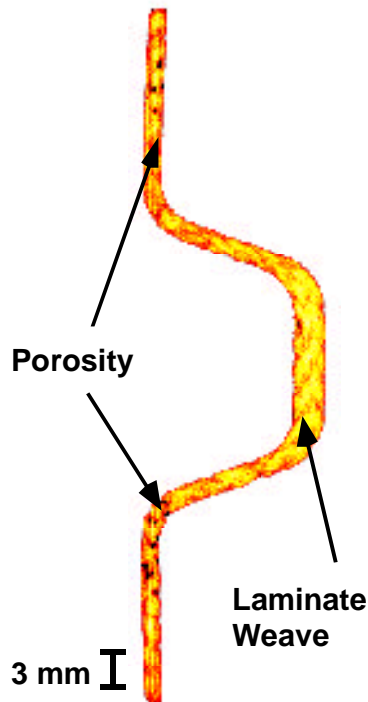
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Table 1. Comparison of normalized stiffness coefficients for unaged thermoplastic panels and panels aged for 10,000 hours at elevated strain and temp.

16 ply Thermoplastic		
Normlized Stiffness	Unaged	10,000 Hrs High Strain
A ₅₅	0.95 ± 0.02	0.84 ± 0.02
D ₁₁	0.69 ± 0.05	0.74 ± 0.10
A ₄₄	0.94 ± 0.03	0.88 ± 0.02
D ₂₂	0.89 ± 0.07	0.81 ± 0.08

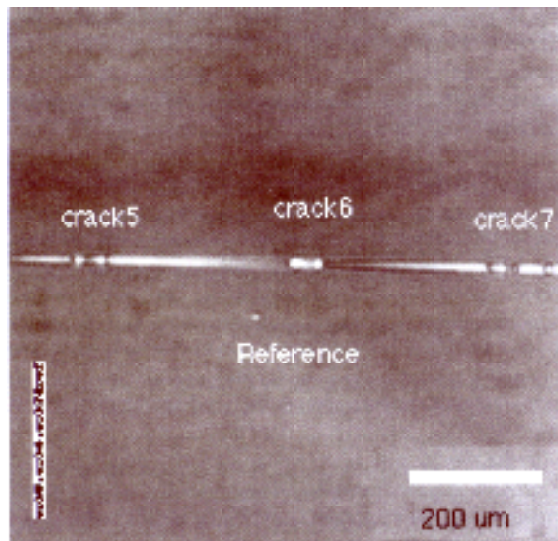


a)



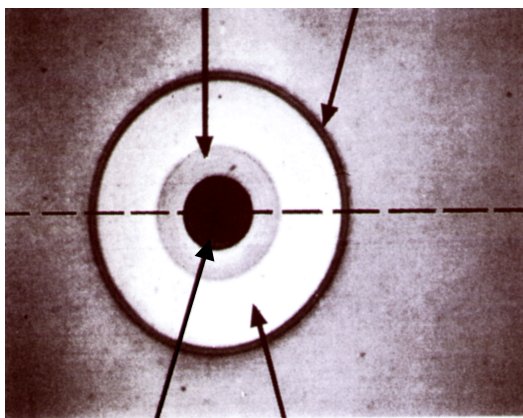
b)

Figure 1. Two microfocus x-ray CT images of composites. These images show detailed microstructural features. Fig.1a shows a composite y-stiffener with impact damage. Cracks and delaminations are visible. Fig.1b shows a composite hat stiffener with porosity. The laminate weave is also visible.



a)

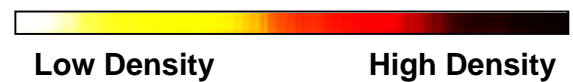
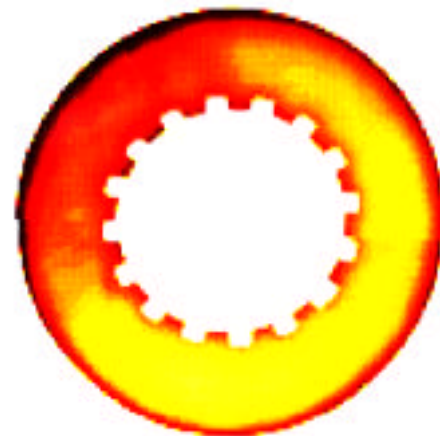
**Carbon diffused
silicon carbide zone Carbon coatings**



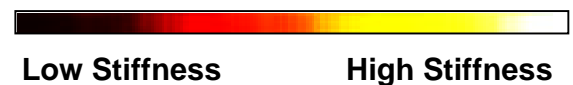
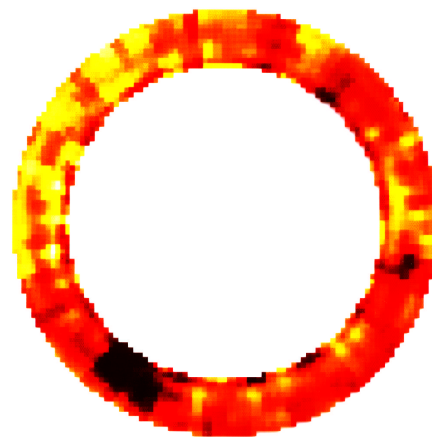
Carbon core Silicon Carbide

b)

Figure 2. Two SAM images of composite fibers. Fig. 2a shows fiber fractures in a single fiber. The ends of the fibers are visible and therefore, the lengths can be measured. Fig. 2b shows a cross section of a silicon carbide fiber from which material properties can be measured.



a)



b)

Figure 3. Radiograph and stiffness image of a carbon-carbon brake stator. Fig. 3a) shows a radiograph of the part. Fig 3b) shows an image of the C_{33} stiffness coefficients for the brake stator. An anomalous area of low stiffness is evident in the lower left region of the image.



Unaged

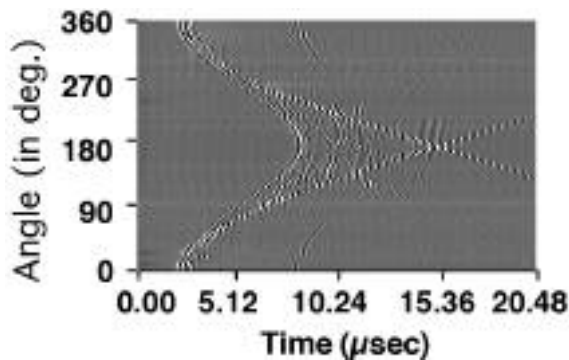


Aged 10,000 hrs., High Strain

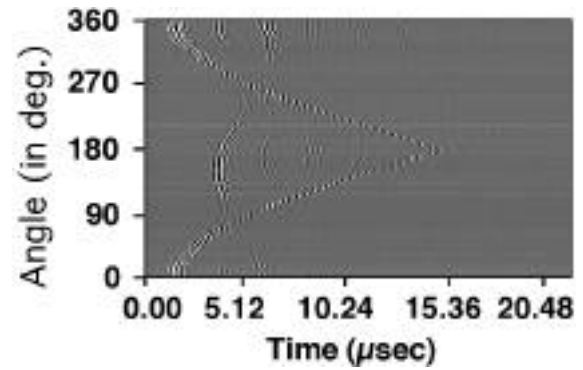
1.00  0.78

Normalized A₅₅ Stiffness

Figure 4. Normalized A₅₅ stiffness images. Top image is from an unaged thermoplastic composite plate. Bottom image is from a thermoplastic composite plate aged for 10,000 hours while undergoing high strain and temperatures flight cycles.

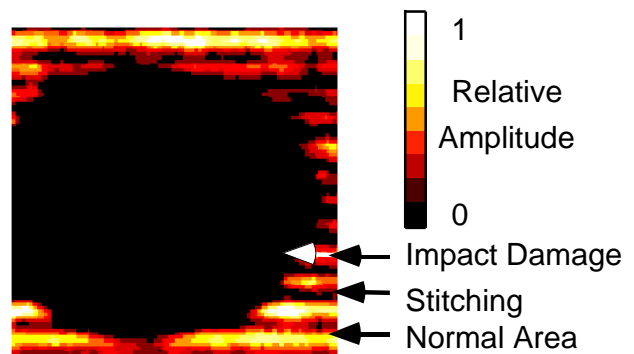


a)



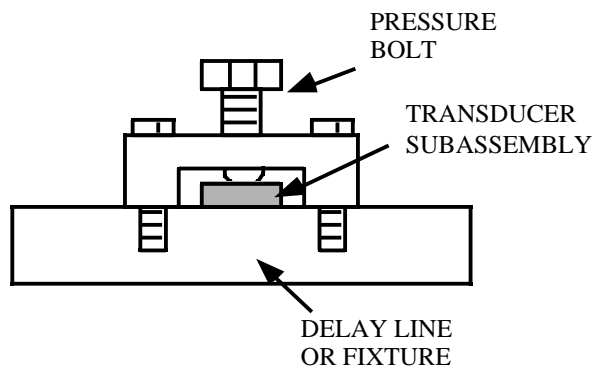
b)

Figure 5. Images of ultrasonic scattering fields. Images were made with a ring phased array. Fig. 5a shows the amplitude of the scattering fields as a function of the angle vs. time for the case where the sound is transmitted into a composite perpendicular to the fibers. Fig. 5b shows the scattering fields as a function of angle vs. time for the case where the sound is transmitted into a composite parallel to the fibers.

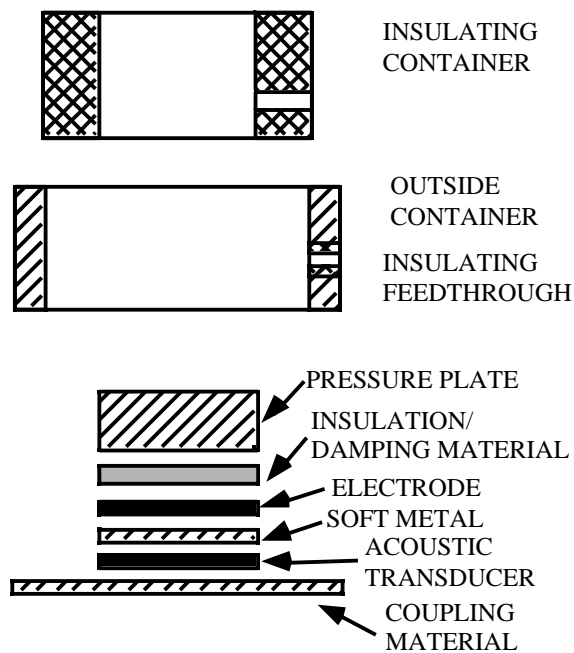


Scan area approximately 2.5 inches

Figure 6. Laser Ultrasound of an impact damaged composite. This image shows the impact damaged area and the regions of stitching.



a)



b)

Figure 7. Images of a high temperature ultrasonic transducer. Fig. 7a shows the transducer assembly. Fig. 7b shows the high temperature probe subassembly.

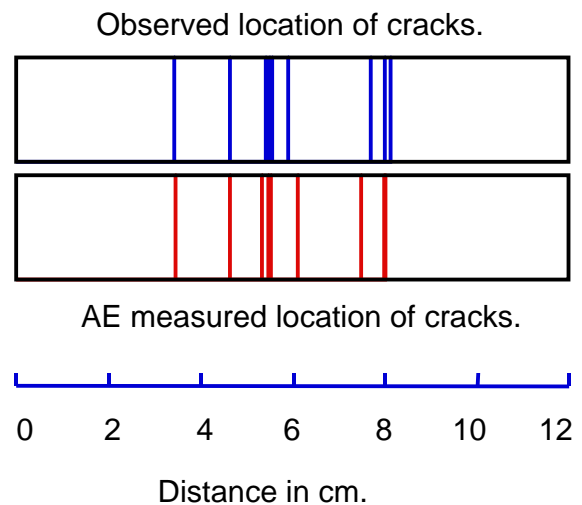


Figure 8. Comparison between AE and visual crack locating methods.

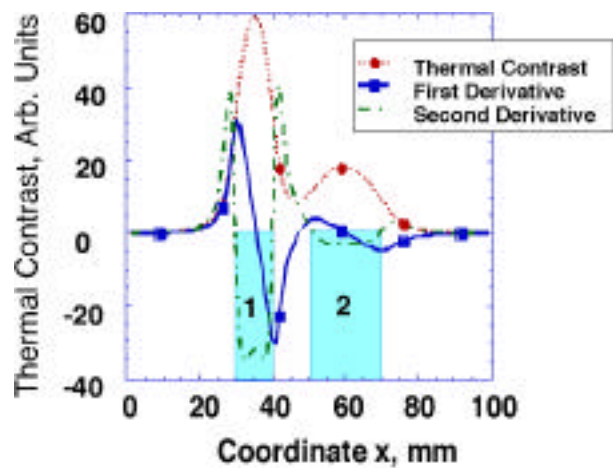
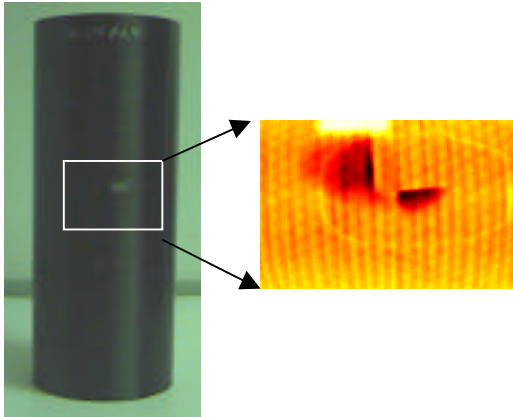
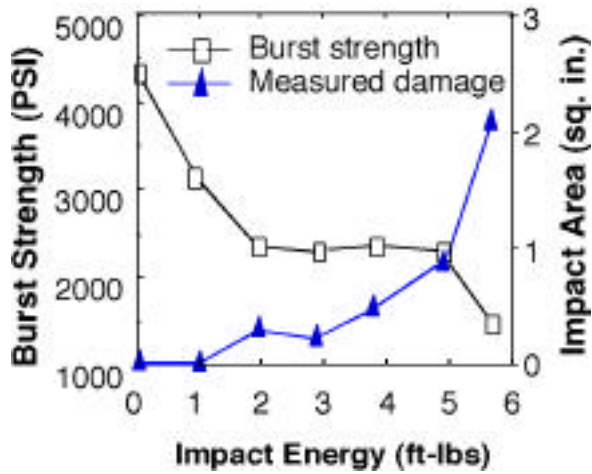


Figure 9. Theoretical modeling of thermal contrast. The shaded areas represent flaws that are one and two inches across. Several methods were investigated to see which method was most accurate in predicting the damage area.



a)



b)

Figure 10. Thermal imaging of damage and comparison between impact damage burst strength and impact energy. Fig. 10a shows a thermal image of an impact area on a composite missile tube. Fig. 10b shows the relationship between burst strength, thermally measured damage and impact energy.

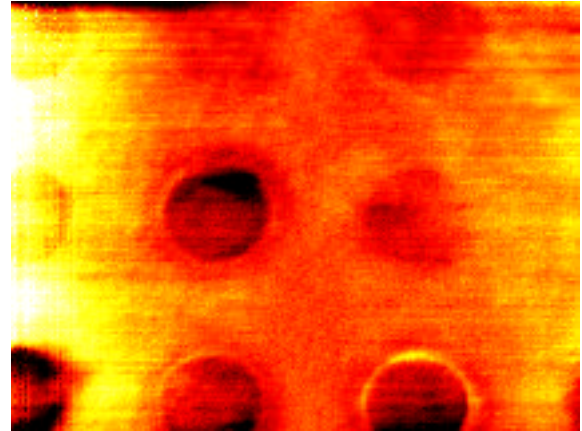


Figure 11. Thermal diffusivity imaging of porosity. The circular regions, which are 2" in diameter, represent hollow microsphere inclusions as a model for porosity. Each region is a different quantity of porosity

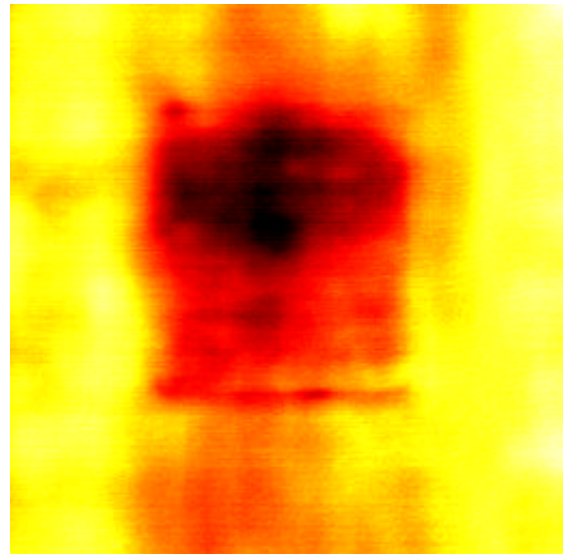
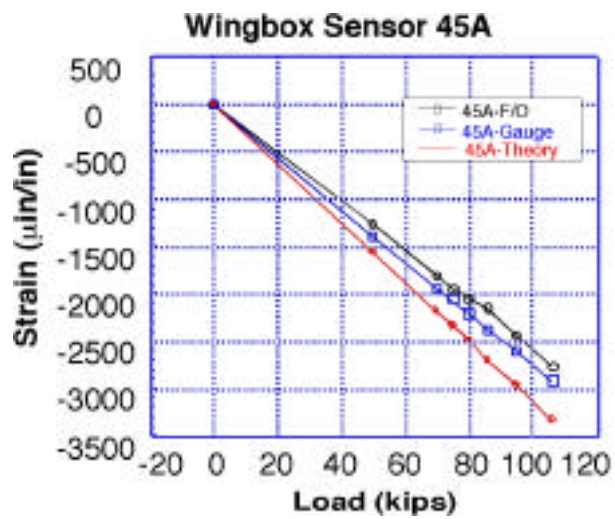


Figure 12. Thermal diffusivity imaging of cut fibers. The dark region is an area of lower thermal diffusivity that resulted from having the graphite fibers cut in a 1.5 inch square area.



a)



b)

Figure 13. A wing box being tested and a comparison of optical and mechanical strain gauges. Fig. 13a shows the wing box to which fiber optic strain gauges were attached. Fig. 13b shows comparison between theory, a mechanical strain gauge, and a fiber optic strain gauge measured during the wing box test.